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Development of an efficient structural system against the progressive collapse of explosive loads for protective measures

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ABSTRACT: Progressive collapse can be caused by the failure and instability of a small part of the structure that gradually develops as a chain function and eventually leads to the collapse of an important part of the structure. Progressive collapse may happen due to explosion, fire, earthquake, vehicle collision and errors in the design and construction of building with any system type. Reinforced concrete (RC) load-bearing wall system is one of the appropriate structural systems for average height buildings that Based on the number of walls in plan and reduction in lateral force contribution, this system in addition to its strength against earthquake, according to volume of construction materials is economical. It can be constructed with high speed, accuracy, and quality. In this thesis, the effect of progressive collapse on the RC load-bearing wall system has been studied and its performance is compared to the RC moment frame. For this purpose, three-dimensional models of 10-story structures with the same plan in both systems, have been selected. The effects of geometric and material nonlinearity are considered and cross sections are modeled by fiber elements. To ensure the accuracy of modeling by fiber section method, the analysis results are validated by an experimental model of RC load-bearing wall.

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1. INTRODUCTION

An explosion or a vehicle-column crash may remove the column instantaneously. The present study attempts to model the gradual removal of the column. Moreover, the result would be compared the findings in the scenario of instantaneous removal of column. Decreasing strength in terms of stiffness is modeled as the gradual removal, and the modeling concept considered for this phenomenon is a gradual reduction in stiffness of the reinforced concrete cross-section affected by fire. To study the structural behavior, the nonlinear dynamic method was used. Bao et al. (2010) proposed a macro model-based approach to enable post-event progressive collapse analysis of reinforced concrete (RC) frame-wall structures [1]. Shi et al. (2010) proposed a new method for progressive collapse of reinforced (RC) frame structures by considering non-zero initial conditions and initial damage to adjacent structural members under blast loading [2]. Khandelwal et al. (2011) presented a technique termed 'pushdown analysis' that can be used to investigate the robustness of building systems by computing residual capacity and establishing collapse modes of a damaged structure [3]. Li et al. (2011) proposed a new tie force method for progressive collapse resistance design of reinforced concrete frame structures [4]. The applicability and reliability of the proposed method is verified through numerical design examples. Salem et al. (2011) presented a three-dimensional discrete crack model based on the applied element method that is used to perform economic design for reinforced concrete structures against progressive collapse [5]. Sasani et al. (2011) proposed a method for finite element modeling and analysis of RC elements that accounts for bar fracture [6]. Fang (2012) describes recent developments in the performance-based design of multi-story buildings against progressive collapse due to localized fire [7]. Kai et al. (2012) carried out experimental and analytical studies on RC moment-resisting frame after it is subjected to the loss of its ground-story exterior column [8]. Szuladzinski (2012) investigated the creation of a set of engineering formulas approximating structure response to a loss of one of supporting columns [9]. Tsai (2012) used linear and nonlinear static procedures for evaluating the alternative load paths of building frames under column loss conditions were refined in the latest UFC 4-023-03 in 2009 [10, 11]. For this purpose, static and dynamic analyses are carried out for several moment-resisting frames subjected to column loss and accuracy of the analytical formulae in predicting the collapse resistance is also demonstrated. Pachenari et al. (2013) evaluated the influence of some external and corner column removal cases by nonlinear procedures in all stories of a regular structure based on the acceptance criteria of UFC 4-023-03 [12]. Qian et al. (2011) studied the vulnerability of conventional RC structures to structural failure caused by the

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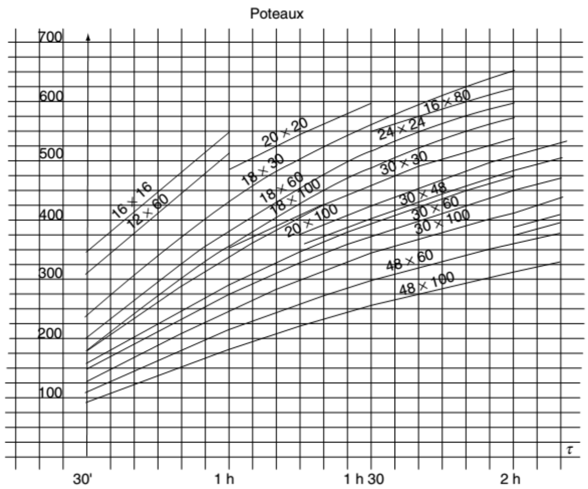

Fig. 1. Temperature of reinforced concrete section versus time during fire

Table 1. Stiffness ratio of secondary columns to the main column

Time (Hour)	Temperature (°C)	Concrete strength reduction factor	Bar strength reduction factor	Stiffness ratio of secondary column to main column
0.5	105	1	1	0
1	225	1	1	0
1.5	325	0.88	1	6.05
2	350	0.84	1	2.11
3	400	0.77	1	4.38
3.5	450	0.67	0.76	4.61
4	500	0.61	0.53	4.88
4.5	550	0.53	0.29	5.21
5	600	0.45	0.13	5.61
5.5	650	0.39	0.09	4.41
6	700	0.34	0.05	4.65
6.5	750	0.28	0	5.06
7	800	0.23	0	5.60
7.5	850	0.17	0	6.36
8	900	0.11	0	7.54
8.5	950	0.06	0	9.82
9	975	0.03	0	6.95
9.5	1000	0	0	16.76

loss of corner columns [13]. The experimental results were compared with the DoD design guidelines to highlight the deficiencies of the recently updated guidelines.

2. MODELING PROCEDURE FOR COLUMN REMOVALS

Figure 4 shows temperature variations for different dimensions of the sections. The dimensions are in centimeters and the time is shown in hours. To model the gradual removal of the column, first, the column is replaced with several parallel secondary columns with equivalent total axial and flexural stiffness. The coordinates of nodes at either end of the secondary columns are the same as that of the main column. Removal of a secondary column at a certain time represents reduction in stiffness of the reinforced concrete section due to fire up to the same time. The secondary columns are arranged in a way that removal of the last secondary column means total failure of concrete section in fire under vertical load. Therefore, the characteristics of the secondary columns are defined based on strength reduction functions of concrete sections due to fire and the temperature-time curve for the reinforced concrete section (Figure 4). Discretizing the time, the temperature caused by fire is read using Figure 4 and dimensions of the section. In the next step, using the temperature obtained in the previous step and the abovementioned functions, strength reduction factors for concrete.

Given the code formula for calculating concrete modulus of elasticity, it is concluded that the modulus of elasticity is directly related to the square root of compressive strength of concrete and keeping in mind that axial (EA) and flexural stiffness (EI) are reduced when the structure is on fire, the decrease in modulus of elasticity during fire is represented by gradual change in cross-section and moment of inertia. As a result omitting the right number of secondary columns at right time would be resembling the gradual deterioration of column axial and flexural stiffness. In this way, time characteristics of secondary columns representing cross-section and moment of inertia are obtained, respectively. Given the description provided above, the ratio of secondary column stiffness to that of the main column (stiffness ratio) is presented in Table 4. Secondary columns are removed in the same manner as instantaneous removal. First, stiffness ratios are used to calculate the internal force of each secondary column, and then the forces are removed at predetermined points in time (forces equal reaction of each secondary column exerted in opposite directions).

3. PROGRESSIVE COLLAPSE ANALYSIS

In this part of the research, the modeling procedure for progressive collapse is caused by the gradual reduction in stiffness of the column, or in other words, the gradual removal of the column is examined. Progressive collapse has been studied based on strength reduction of columns

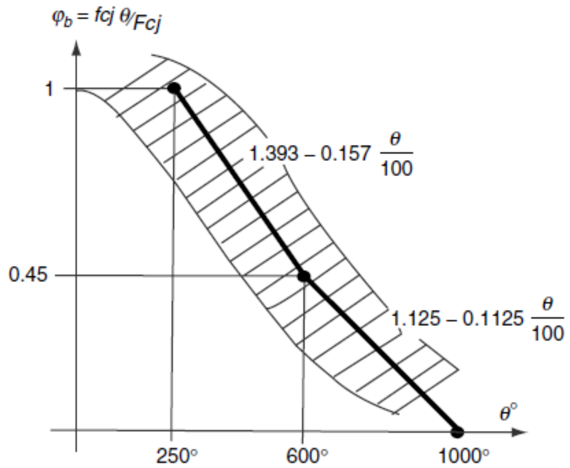

Fig. 2. Concrete strength reduction factor versus temperature of fire

affected by fire. Figure 2 shows the concrete strength reduction factor which is defined as the ratio of compressive strength of concrete at a certain temperature of fire to its basic compressive strength. The bars at the reinforced concrete section suffer from a reduction in strength due to fire. The procedure of nonlinear dynamic analysis for modeling the instantaneous removal of columns in a structure is described. First, static analysis is performed under gravity loads and then internal forces in the column to be removed through progressive collapse are determined. In the next step, the column is removed from the model and replaced by the reaction force at the top of the column. Once again, static analysis is performed under gravity loads. It has been verified that the results of this analysis are the same as the results of the previous analysis (prior to removing the column). Instantaneous removal is modeled by dynamic analysis in a case where forces equal to the reaction of the removed column are instantaneously exerted on the model in the opposite direction as an impulse.

4. MODELING ASSUMPTIONS IN SAP2000

Confined and unconfined concrete and nonlinear steel in SAP2000 were used to model concrete and steel, respectively. Table 5 shows the parameters used for cover and core concretes. The strain hardening factor for Steel was set at b = 0.01. All nonlinear beam-columns have elastic torsional stiffness, which is aggregated to fiber sections. Torsional stiffness for each section is equal to G×J where G is the concrete modulus of torsion and J is the torsional moment of inertia calculated based on dimensions of the sections. Service loads for progressive collapse analysis of structures are calculated based on GSA guideline [14]. Load factors of 1 and 0.25 are used for dead load and live load, respectively. These loads are applied to each node of the structure according to the node tributary area. Column and beam weights are applied to each node of the structure according to the tributary lengths. Obviously, progressive collapse is caused by removal of column results in major rotations and deformations in the structure, and particularly in the elements adjacent to the removed columns. For precise modeling of structural behavior, large deformations in elements were analyzed using the co-rotational coordinate system. The system geometrically transforms the stiffness of beams and resisting forces from the basic system to the global coordinate system. In this approach, rigid deformation is subtracted from total deformation. It is assumed that remaining deformations lead to strains in the updated local axis system of elements which, in turn, results in plastic deformation in the elements. Therefore, in addition to nonlinear behavior which was included in the model based on the definition of nonlinear stress-strain relationships for concrete and steel fibers, geometric nonlinearity is also applied to the model using co-rotational coordinate system.

5. RESULTS

Methods of reducing the rate of fire lead to demand (stress and deformation) reduction in structure particularly in adjacent elements of the zone of fire. Dynamic amplification effects caused by instantaneous removal of the column lead to a higher demand for stress and deformation in the structure compared to gradual removal of the column. Vertical displacement of the upper node of columns after gradual removal is 70 to 78 percent of the maximum vertical displacement after instantaneous removal. In the instantaneous scenario, maximum axial forces at adjacent columns of the removed column are two to five percent greater than the forces exerted in the gradual scenario, while at the equilibrium, the axial load on adjacent columns of the removed column in instantaneous cases are the same as respective values in gradual cases with 1 percent difference. The increased force exerted on adjacent columns after the removal of the column exceeds the axial force exerted on this column before the removal. This can be the result of reduction in axial load or reloading on adjacent columns when the column is removed. In both scenarios, the percentage of increase in axial forces of adjacent columns of the removed column at the end of the analysis (equilibrium state) compared to the same value prior to removal of the column, which reflects the contribution of each column in redistribution of forces bore by the removed column is equal to 1 percent difference. Maximum bending moment at the adjacent beams of the removed column in the instantaneous scenario are 6 to 10 percent larger than the bending moments in the gradual scenario, while at the equilibrium, bending moment at the adjacent beams of the removed column in the instantaneous scenario are the same as the values obtained in the gradual scenario with 2 percent difference. Plastic deformation in the adjacent beams of the removed column in gradual removal is 70 to 73 percent of the plastic deformation in the instantaneous removal. The stresses caused in the bottom bars of the adjacent beams of the removed column in the gradual scenario are 80 to 96 percent of the stresses in the gradual case. Damping selected for gradual removal has no effect on the results, while the results obtained in the instantaneous scenario are damping dependent. Setting damping ratio at its minimum value results in a more critical analysis. This means that larger forces and displacements occur in the structure after removal of the column. If the tensile strength of concrete is considered in the analysis, demand for force and deformation decreases. As a result, if the tensile strength of the concrete is assumed to be zero, it would lead to a conservative assumption in the analysis.

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